A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:

ASTRONOMY AND ASTROPHYSICS
20.7.2001

Are some breaks in GRB afterglows caused by their spectra?

D.M. Wei[1,2], and T. Lu[3,4]

[1] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, China
[2] National Astronomical Observatories, Chinese Academy of Sciences, China
[3] Department of Astronomy, Nanjing University, Nanjing, 210093, China
[4] Laboratory for Cosmic-Ray and High-Energy Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100039, China

Received date/ Accepted date

Abstract. Sharp breaks have been observed in the afterglow light curves of several GRBs, and it's generally explained by the jet model. Paczynski has proposed that, if GRBs are at cosmological distances, and if their spectral slopes change gradually, then the weaker bursts should have softer spectra than the stronger bursts. Here we first analyzed the relation between the gamma-ray bursts fluence and the hardness ratio, and found that, there is no correlation for all bursts, while for either long duration or short duration bursts, their hardness ratio increase with the fluence, which implies that the longer and short bursts are different. Then we assume the emission spectra of bursts and their afterglow are not an exact power law, the slopes changes smoothly, $d\beta/dlog\nu < 0$, where β is the spectral index, we found that this spectra can fit the afterglow light curves with breaks very well. Therefore we suggest that some breaks in the afterglow light curves may be caused by their curved spectra. The main feature of this interpretation is that the break time is dependent on the observed frequency, while the jet model produces the achromatic breaks in the light curves.

Key words: gamma rays: bursts

1. Introduction

It is widely accepted that the emission from GRB afterglows can be well described by the fireball model, in which the ejecta from an underlying explosion expands into the surrounding medium to produce relativistic shock(e.g. Piran 1999 and references therein). In the standard picture, the electrons are accelerated to relativistic energies, with their Lorentz factors described by a simple power law distribution $f(\gamma_e) \propto \gamma_e^{-p}$ above the minimum value γ_m. Besides particle acceleration, the shock is also responsible for the creation of strong magnetic field. Under these conditions the electrons radiate synchrotron emission with the afterglow flux $f(t,\nu) \propto t^{\alpha}\nu^{\beta}$, where the temporal index (α) and the spectral index (β) are related to p and the dynamics of the blast wave (Wijers, Rees & Meszaros 1997; Wei & Lu 1998; Sari, Piran & Narayan 1998; Huang et al. 2000). In the standard case, where the blast wave is isotropic and adiabatic, $\alpha = \frac{3}{2}\beta$.

The optical light curves of afterglows can generally be described by a single power law with indices $\alpha \simeq 1.1 - 2$. However, the changes in the light decay rate have been detected in several GRBs with a transition to a steeper power law behavior (GRB990123: Kulkarni et al. 1999; GRB990510: Harrison et al. 1999, Stanek et al. 1999; GRB000301C: Rhoads & Fruchter 2000, Masetti et al. 2000; GRB000926: Sagar et al. 2000; GRB010222: Masetti et al. 2001, Stanek et al. 2001, Cowsik et al. 2001). Such breaks are usually explained by the jet model. Rhoads (1997; 1999) has pointed out that the lateral expansion of the relativistic jet will cause a change in the hydrodynamic behavior and hence a break in the light curve. However, in fact, jet evolution and emission is a very complicated process, the different analytic or semi-analytic calculations have different predictions for the sharpness of the jet break, the jet break time and the duration of the transition. For example, Rhoads (1999) claimed that jet expansion will produce sharp breaks in the light curves, while some numerical calculations show that the breaks are smoothly and gradually (Panaitescu & Meszaros 1999; Moderski, Sikora & Bulik 2000; Kumar & Panaitescu 2000; Wei & Lu 2000a,b). In particular, the light curve of GRB010222 seems difficult to be explained by the jet model (Masetti et al. 2001; Dai & Cheng 2001).

Paczynski (1992) proposed that, if GRBs are at cosmological distances, and if the spectral slope changes in the same direction, $d\beta/dlog\nu < 0$, then the weakest bursts should have softer spectra than the strongest. In section 2 we analyze the relation between the bursts fluence and their hardness ratio, and find that the results support the Paczynski's proposition. In section 3 we discuss the effect of the curved spectra on the afterglow light curves, find that the light curves with sharp break can be fitted very well. Finally some discussions and conclusions are given.

2. The fluence-hardness ratio relation

In 1992 when it is unclear whether GRBs are at cosmological distances or in our Galaxy, Paczynski proposed a very simple way to estimate the distance scale (Paczynski 1992). Giving two simple assumptions: (1) the GRBs are at cosmological distances, (2) the emission spectra do not follow perfect power laws, then he concluded that the weakest bursts should have soft spectra than the strongest.

The BATSE observations have provided a wealth of data to study the statistical properties of GRBs. The fourth GRB catalog (4B) contains gamma-ray bursts between 19 April, 1991 and 29 August, 1996. The 4B-flux table gives the fluences of total 1292 bursts in four energy channels, the channel 1,2,3 and 4 fluences cover the energy ranges 20-50 KeV, 50-100 KeV, 100-300 KeV, and $E > 300\,KeV$ respectively. Here we define the hardness ratio = fluence($> 300\,KeV$)/fluence(50-100 KeV), and the total fluence to be the sum of four channel fluences. We first use the total bursts to check the hardness ratio-fluence relation, but find that there is no correlation between them.

It is well known that the duration distribution of gamma-ray bursts is of bimodality, which separates GRBs into two classes: short events ($< 2\,s$) and longer ones ($> 2\,s$)(Kouveliotou et al. 1993). So we choose two groups of bursts: the longer one with duration $T_{90} > 10\,s$ and the short one with duration $T_{90} < 1\,s$, where T_{90} is the time during which the cumulative counts increase from 5% to 95% above background, thus encompassing 90% of the total GRB counts. Fig.1 gives their hardness ratio-fluence relation. It is very interesting that, for both longer bursts and short bursts, there is a positive correlation between the hardness ratio and fluence, i.e. weaker bursts have softer spectra, which confirms the Paczynski's prediction. Now from afterglow observations it is clear that GRBs are at cosmological distances, so it is reasonable to conclude that the spectra of gamma-ray bursts do not follow perfect power laws, their spectra may be curved.

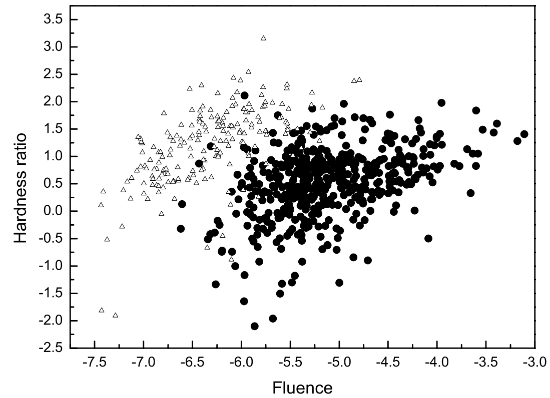

Fig. 1. The hardness ratio-fluence relation. The solid circles are longer bursts, and the open triangles are short bursts.

3. The effect of curved spectra on afterglow light curve

In the standard picture, it is assumed that the distribution of energetic electrons is described by a simple power law $f(\gamma_e) \propto \gamma_e^{-p}$ above the minimum value γ_m, and their emission spectra is also a single power law with index $\beta = -(p-1)/2$. However, it may be not the truth. In the previous section we have shown that the hardness ratio-fluence relation suggests the bursts' spectra may be not a simple power law. In addition, the direct observations of GRBs' spectra also indicate that many spectra seem to be curved, it is well known that many spectra can be fitted by thermal bremsstrahlung, thermal synchrotron or Comptonized spectra very well (Higdon & Lingenfelter 1990). It seems that the slope of the spectra changes in the same direction, $d\beta/dlog\nu < 0$, where the spectral index β defined as $\beta = dlogF_\nu/d\log\nu$.

The simplest form of a spectrum with a slowly changing slope is (Paczynski 1992)

$$F_\nu = F_{\nu_m}(\nu/\nu_m)^{-(\beta_1+\frac{1}{2}\beta_2\log(\nu/\nu_m))} \quad for \;\; \nu > \nu_m \tag{1}$$

where ν_m is the emission frequency corresponding to the minimum electron Lorentz factor γ_m, F_{ν_m} is the peak flux at ν_m. Then the spectral slope is given by

$$\beta = dlogF_\nu/d\log\nu = -(\beta_1 + \beta_2\log(\nu/\nu_m)) \tag{2}$$

Now let us consider the standard case, i.e. the blast wave is isotropic and adiabatic, the surrounding medium is homogeneous, and the afterglow emission is mainly produced by the synchrotron radiation of the accelerated electrons. Under these conditions, the evolution of the bulk Lorentz factor is $\Gamma \propto t^{-3/8}$, the peak flux $F_{\nu_m} \propto t^0$, and $\nu_m \propto t^{-3/2}$ (e.g. Piran 1999 and references therein). Then for a fixed frequency ν_{obs}, the afterglow light curve is

$$F_{\nu_{obs}} \propto t^{-\frac{3}{2}(\beta_1+\frac{3}{4}\beta_2\log(t/t_m))} \quad for \;\; t > t_m \tag{3}$$

where t_m is the time when ν_m crosses the fixed frequency ν_{obs}.

Based on the above results, we have fitted five GRBs' afterglow light curves, in which the sharp breaks are present. From Fig.2 - Fig.6, we see that this model can fit the observed data very well.

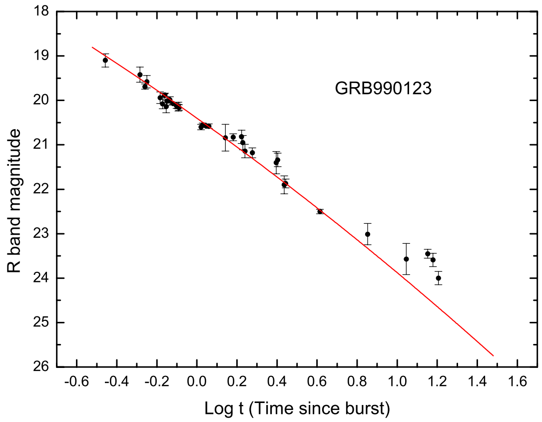

Fig. 2. The afterglow light curve of GRB990123, the solid line is our fitted results, the parameters are: $\beta_1 = 0.8$, $\beta_2 = 0.1$, $t_m = 0.2\,day$.

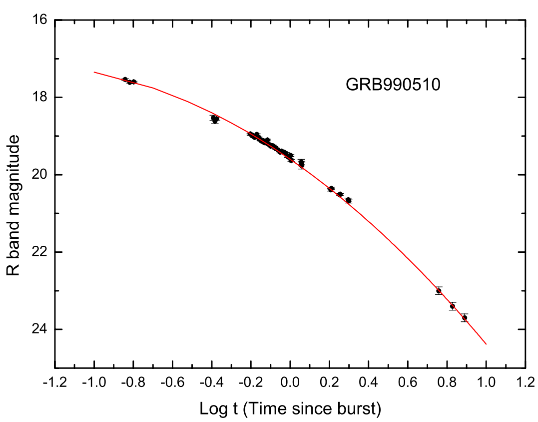

Fig. 3. The afterglow light curve of GRB990510, the solid line is our fitted results, the parameters are: $\beta_1 = 0.6$, $\beta_2 = 0.45$, $t_m = 0.1\,day$.

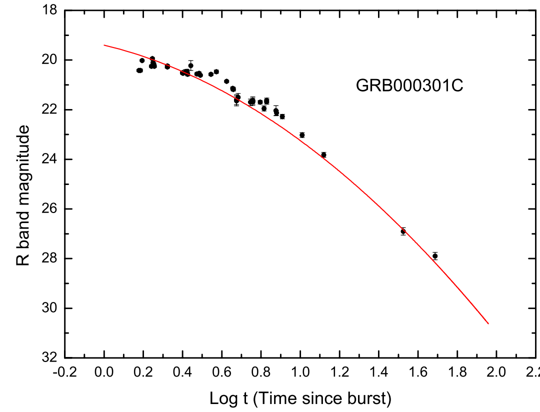

Fig. 4. The afterglow light curve of GRB000301C, the solid line is our fitted results, the parameters are: $\beta_1 = 0.5$, $\beta_2 = 0.7$, $t_m = 1\,day$.

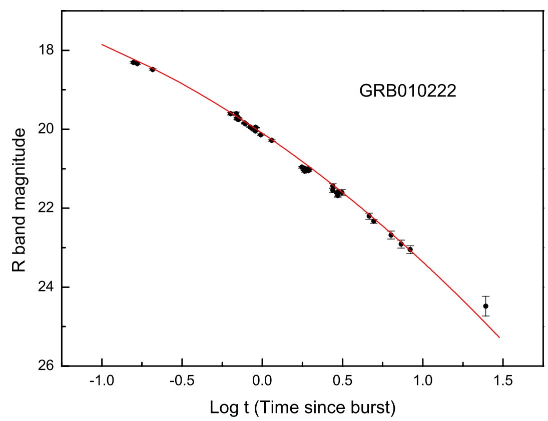

Fig. 5. The afterglow light curve of GRB010222, the solid line is our fitted results, the parameters are: $\beta_1 = 0.6$, $\beta_2 = 0.15$, $t_m = 0.1\,day$.

4. Discussion and conclusions

In this Letter, we first analyze the relation between the hardness ratio and the bursts' fluence. It is very interesting to note that, if we put the all bursts together, there is no correlation, however, if we take long duration bursts and short duration bursts, then there is positive correlation for either longer or short bursts: the weaker bursts have softer spectra. It is well known that the identification of two classes of GRBs (long and short duration) is originated from the duration distribution, now we propose that the hardness ratio - fluence distribution (Fig.1) gives another evidence that there are two classes of GRBs.

From the hardness ratio - fluence distribution, it is reasonable to think that the spectra of bursts and their afterglow are not a simple power law, the spectral index changes gradually with frequency. Under these conditions, we have shown that, even in the standard afterglow model, the afterglow light curves with sharp break can be fitted very well, and the values of the parameter β_2, which determine the sharpness of the spectra and light curves, are generally less than 1 (can be even small as 0.1). so we propose that the effects of the curved spectra on the light curves should not be ignored.

For the simple spectral form we adopted here(equation 1), the relation between the temporal index (α) and the spectral index (β) is $\alpha = \frac{3}{2}\beta$, and for the fixed frequency ν_{obs}, the spectral index (β) changes with time, so it is im-

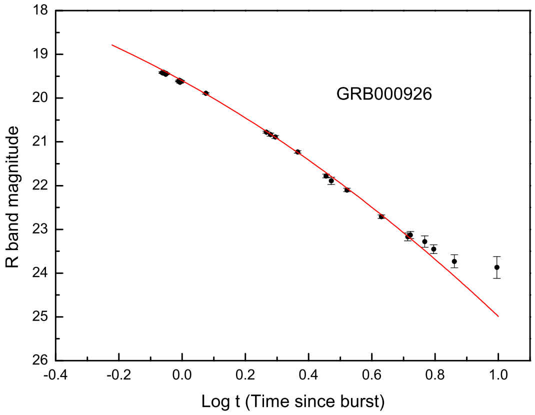

Fig. 6. The afterglow light curve of GRB000926, the solid line is our fitted results, the parameters are: $\beta_1 = 0.8$, $\beta_2 = 0.5$, $t_m = 0.2\,day$.

portant to measure the spectral evolution in the afterglow observation. In addition, it is also necessary to improve the detectors' energy resolution so as to measure the small curvature of the spectra.

The main feature of this interpretation is that the break time is dependent on the observed frequency, i.e. the break time is larger for smaller frequency, while for jet model (Rhoads 1999) or transition from relativistic to non-relativistic (Dai & Lu 1999), the break time are achromatic, so it is easy to distinguish between them.

In summary, here we propose that the positive correlation between the hardness ratio and fluence for either longer or short bursts gives an evidence that the GRBs have two classes. Furthermore we show that the small curvature in the spectra can produce sharp break in the afterglow light curves. So it is important to measure the spectral evolution and curvature in the future observation.

Acknowledgements. This work is supported by the National Natural Science Foundation (10073022 and 19973003) and the National 973 Project on Fundamental Researches of China (NKBRSF G19990754).

References

Cowsik, R., et al., 2001, astro-ph/0104363
Dai, Z.G., Lu, T., 1999, ApJ, 519, L155
Dai,Z.G., Cheng, K.S., 2001, astro-ph/0105055
Harrison, F.A., et al., 1999, ApJ, 523, 121
Higdon, J.C., Lingenfelter, R.E., 1990, ARA&A, 28, 401
Huang, Y.F., et al., 2000, ApJ, 543, 90
Kouveliotou, C., et al., 1993, ApJ, L101
Kulkarni, S.R., et al., 1999, Nature, 398, 389
Kumar, P., Panatescu, A., 2000, ApJ, L9
Masetti, N., et al., 2000, astro-ph/0004186
Masetti, N., et al., 2001, astro-ph/0103296
Moderski, R., Sikora, M., Bulik, T., 2000, ApJ, 529, 151
Paczynski, B., 1992, Nature, 355, 521
Panaitescu, A., Mészáros, P., 1999, ApJ, 526, 707
Piran, T., 1999, Phys. Rep., 314, 575
Rhoads, J.E., 1997, ApJ, 487, L1
Rhoads,J.E., 1999, ApJ, 525, 737
Rhoads,J.E., Fruchter, A.S., 2000, astro-ph/0004057
Sagar, R., et al., 2000, astro-ph/0010212
Sari, R., Piran, T., Narayan, R., 1998, ApJ, 497, L17
Stanek, K.Z., et al., 1999, ApJ, 522, L39
Stanek, K.Z., et al., 2001, astro-ph/0104329
Wei, D.M., Lu, T., 1998, ApJ, 499, 754
Wei, D.M., Lu, T., 2000a, ApJ, 541, 203
Wei, D.M., LU, T., 2000b, astro-ph/0012007
Wijers, R.A.M.J., Rees, M.J., Mészáros, P., 1997, MNRAS, 288, L51

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.